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Low-energy Coulomb excitation of ^{94}Zr

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Summary. — Recent state-of-the-art Monte Carlo shell-model calculations predict shape coexistence in Zr isotopes. In this context, the ^{94}Zr nucleus is particularly interesting since some experimental investigations have already suggested the possible coexistence of spherical and oblate shapes, however, no definitive conclusion on its deformation has been reported to date. As such, a dedicated experiment to study collectivity and configuration coexistence in ^{94}Zr by means of a low-energy Coulomb excitation was performed. This study was performed at the INFN Legnaro National Laboratory with the GALILEO-SPIDER setup, which, in this instance, was further augmented with 6 Lanthanum Bromide scintillators ($LaBr_3$:Ce) in order to to maximize the γ-ray detection efficiency.

1. – Introduction

The observation that an atomic nucleus may exhibit eigenstates with different shapes at similar excitation energies is a widespread phenomenon that is now thought to occur in nearly all nuclei [1]. However, a complete description of this characteristic feature, *i.e.* shape coexistence, is still missing. An additional motivation for the study of shape coexistence arises due to its sensitivity to the proton-neutron interaction within the nucleus, the knowledge of which is of crucial importance for our understanding of nuclear structure.

The zirconium isotopes exhibit a variety of collective behaviour phenomena; in the mid-shell region around $N \sim 40$ they exhibit a deformed shape, progressing to a closed neutron shell configuration at $N = 50$, and then to a sudden reappearance of deformation at $N \sim 60$. It is, therefore, not surprising that the zirconium region has been the subject of intense experimental and theoretical work, in order to study how collectivity evolves in these isotopes and to examine the coexistence observed between various configurations. The ^{94}Zr ($N = 54$) isotope is particularly interesting, because it is thought to be a strong candidate for displaying type-II shell evolution [2], as recently proposed for the zirconium isotopes (around $N = 56$) by state-of-the-art Monte Carlo shell model calculations [3] (see fig. 1).

We have, therefore, performed a dedicated Coulomb-excitation experiment with the aim of investigating the degree of quadrupole deformation both in the ground state and the low-lying excited states of ^{94}Zr. "Safe" Coulomb excitation is a purely electromagnetic process due to the Coulomb field acting between two colliding nuclei. The "safe" energy condition ensures that the contributions of the short-range nuclear force are negligible and, therefore, the experimental results can be obtained in a nuclear-model-independent way. This is fulfilled by maintaining a minimum distance of 5 fm between the nuclear surfaces [4]. The Coulomb-excitation technique preferentially excites low-lying collective nuclear states, offering the possibility to measure observables directly related to the shape of the nucleus at low excitation energy.

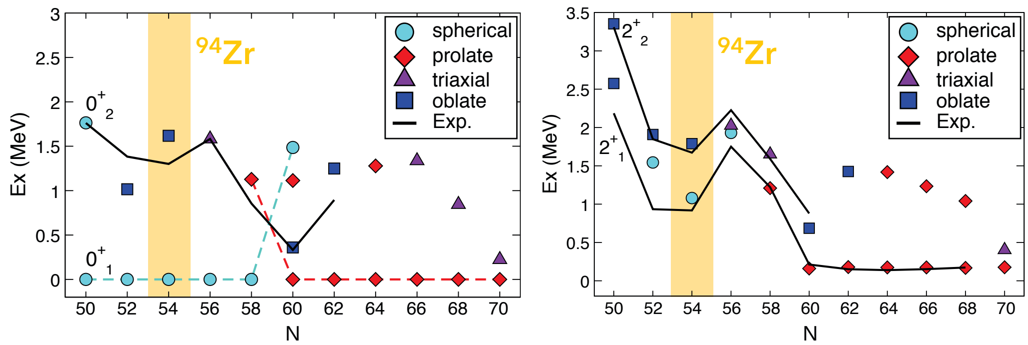

Fig. 1: Experimental (continuous line) and calculated excitation energies (symbols) of the $0^+_{1,2}$ (panel *a*) and $2^+_{1,2}$ (panel *b*) states in Zr isotopes. The symbols indicate the calculated shape of each state. Figure adapted from ref. [3].

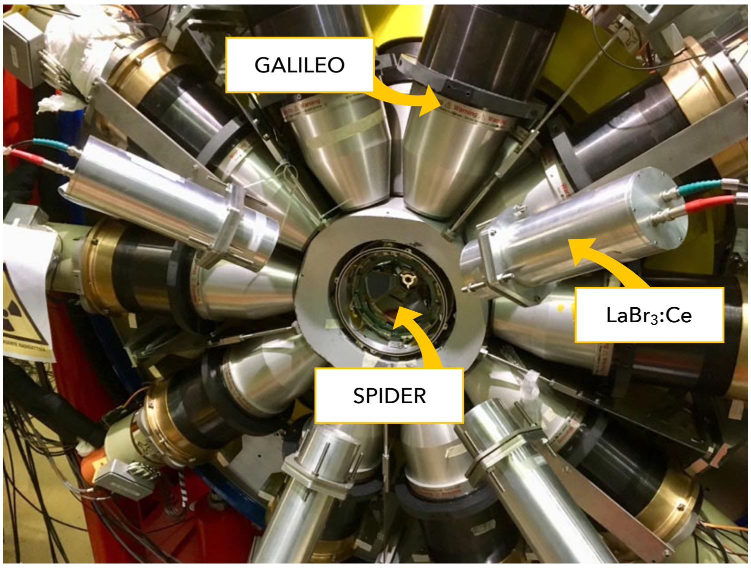

Fig. 2: The experimental setup used for the Coulomb-excitation experiment of ^{94}Zr. The GALILEO array, the SPIDER array and six $LaBr_3$:Ce detectors are shown.

2. – Experiment

The experiment was performed at the Legnaro National Laboratory (LNL) of the National Institute of Nuclear Physics (INFN). A 370-MeV beam of ^{94}Zr ions was impinged onto a 1 mg/cm^2-thick ^{208}Pb target. The GALILEO detector array [5] in conjunction with the recently commissioned SPIDER (Silicon PIe DetectoR) charged-particle detector [6], was used to measure γ rays in coincidence with backscattered ^{94}Zr ions. The GALILEO γ-ray spectrometer consists of 25 Compton-suppressed HPGe detectors arranged into 4 rings at 152°, 129°, 119° and 90° with respect to the beam direction. The SPIDER charged-particle array is composed of 7 segmented Si detectors (each divided into 8 independent strips) assembled in a cone-like shaped configuration. SPIDER was positioned within the GALILEO scattering chamber at backward angles, in order to avoid excessive radiation damage. As such, the polar angular coverage ranges from 123 to 163 degrees in the laboratory frame. Six 3"×3" $LaBr_3$:Ce scintillators were also coupled to the GALILEO-SPIDER setup (as shown in fig. 2), in order to increase the γ-ray detection efficiency. The resolution and efficiency of these $LaBr_3$:Ce scintillators, when implemented in the setup, has been studied in detail, providing important information for the planning of future experiments with these detectors [7].

The detection of γ-particle coincidences offers the possibility to have clean, Doppler-corrected γ-ray spectra, to study the properties of the projectile (and/or target) nucleus. As an example, a preliminary γ-ray energy spectrum acquired in coincidence with backscattered ^{94}Zr ions is shown in fig. 3 (about 50% of the total statistics is considered). The observed ^{94}Zr transitions are labelled, together with peaks related to the excitation of the target and its contaminants. Direct and multi-step excitation of the 2^+_1, 4^+_1, 0^+_2, 2^+_2, 2^+_3, 4^+_2, 2^+_4 and 3^-_1 states of ^{94}Zr has been observed. For the $2^+_4 \longrightarrow 2^+_2$, $2^+_4 \longrightarrow 0^+_2$, $4^+_2 \longrightarrow 2^+_2$ transitions it is only possible to consider the sum of all angles covered by

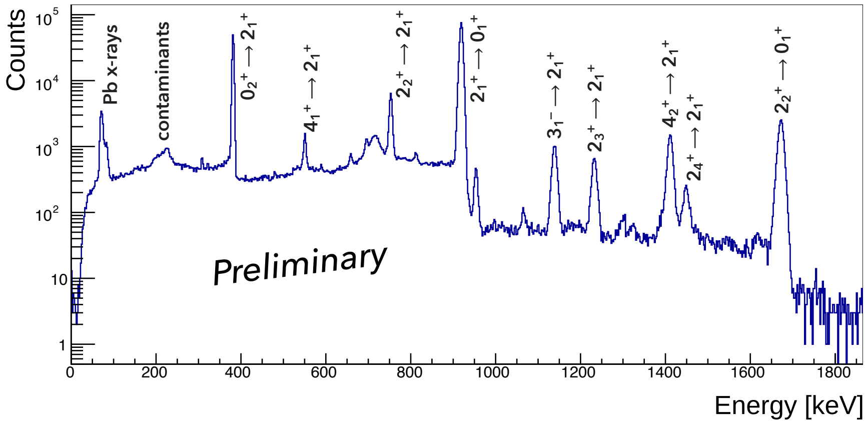

Fig. 3: Spectrum of γ-rays detected by the GALILEO array (without considering the $LaBr_3$:Ce detectors) in coincidence with backscattered ^{94}Zr ions. About 50% of the total statistics is presented.

the SPIDER array in the analysis. However, for other transitions, the observed number of counts is sufficient to divide the statistics into eight different scattering angle ranges, thus exploiting the full segmentation of SPIDER.

All transitions needed to obtain the spectroscopic quadrupole moments of the first two 2^+ states have been observed, as well as those necessary to determine the deformation of the ground state and of the 0_2^+ state. The experimental data are currently being analysed with the least-squares fitting code GOSIA [8]. The code fits a set of reduced matrix elements to the measured γ-ray yields (75 in this experiment) taking into account known spectroscopic data related to electromagnetic matrix elements: branching ratios (10), lifetimes (8), E2/M1 mixing ratios (5). All data have equal weight in the χ^2 function as the γ-ray yields observed in the Coulomb-excitation experiment. A preliminary analysis seems to qualitatively confirm the predictions of Monte Carlo shell model, shown in fig. 1. The present results (even if preliminary) are in agreement with the reduced transition probabilities available in the literature, *e.g.* [9]. This provides confidence that the ongoing analysis will give clear and definitive information on the deformation and shape coexistence in ^{94}Zr.

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